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COMPARISON BETWEEN VS30 AND OTHER ESTIMATES OF SITE AMPLIFICATION IN ITALY

Marco MUCCIARELLI[1], Maria Rosaria GALLIPOLI[2]

SUMMARY

During 5 microzonation projects in Italy, we had access to 46 estimates of Vs30 (30 obtained with down-hole or cross-hole measurements, plus 10 velocity profiles obtained with surface techniques, 6 sites were considered A without drilling, being rock sites). In all the sites we performed HVNR measurements to verify the presence of a resonant frequency and in 34 sites we installed seismic instrumentation to record earthquakes and estimate site amplification using HVSR. It is important to note that we did not pre-selected the sites, but just followed the requests of two Regional governments (Marche and Basilicata) to study a set of localities that were chosen for reasons other than geo-morphological ones (previous earthquakes, pilot studies, design of new infrastructures). The comparison between site seismic amplification and Vs30 showed that this last parameter is not a good proxy of observed site effects. The reason why in Italy Vs30 does not provide satisfactory estimates is linked to peculiar geological settings that are widespread in our country. The main problems encountered are underestimations by Vs30 at sites with velocity inversions and overestimations on deep basins. Vs30 seems to work fine only if a site has a strictly monotonic velocity profile increasing with depth and a strong impedance contrast in the first dozen meters. Further data will be available thanks to an ongoing national project funded by the Civil Defence Department that is focusing on Vs30 estimates in the presence of velocity inversions, fractured rock masses, landslides and karst areas.

1. INTRODUCTION

The average of shear wave velocity in the first 30 m (Vs30) has been internationally adopted since the NEHRP classification in the USA. The original work of Borcherdt (1992) was based on data from Western USA, and so were the first papers discussing pro (Anderson et al, 1996) and cons (Wald & Mori, 2000) of the method. Outside the region where the method was developed, some doubts arose about the capability of Vs30 to predict amplification in deep basins (Park & Hashash, 2004), in other tectonically active regions (Stewart *et al*., 2003) or in presence of a velocity inversion (Di Giacomo *et al.,* 2005).

The Italian seismic code, updated in 2003 largely following the provisions of EuroCode8, has taken for granted the fact that Vs30 can be used without modification also in Italy. The aim of our work is to verify if:

1. Vs30 is a good proxy of site amplification in a country with complex geology
2. The grouping of Vs30 in the Italian Seismic Codes in different soil classes and relevant spectra is adequate

We want to point out that we did not pre-selected the sites where the study was carried out, but we just followed the requests of two Regional governments (Marche and Basilicata) to study a group of sites that were chosen for reasons other than geo-morphological ones (previous earthquakes, pilot studies, design of new infrastructures).

We took into account 30 estimates of Vs30 obtained with down-hole or cross-hole measurements, plus 10 velocity profiles obtained with surface techniques, 6 sites were considered A without drilling, being rock sites). In all the sites we performed HVNR measurements to verify the presence of a resonant frequency and in 34 sites we installed seismic instrumentation to record earthquakes and estimate site amplification. The HVNR was estimated using a digital tromometer (Micromed Tromino) and the same processing technique for all the sites.

[1] DiSGG – Università della Basilicata, Viale dell'Ateneo Lucano 10, 85100 Potenza Italy
Email : mucciarelli@unibas.it
[2] IMAA – CNR, Contrada S.ta Loja, Tito Scalo (PZ) Italy
Email: gallipoli@pz.cnr.it

The earthquakes were recorded with Lennartz 1 Hz seismometers and 24 bits digitisers at 11 sites, with Nanometrics BB station at 4 sites and with Etna Kinemetrics at all the others.

2. DATA ANALYSIS

All the parameters used in the subsequent analyses are reported in Tab. 1. The first column is the name of the site, the second reports the technique used for the estimate of the Vs profiles (H= down-hole or cross-hole, S= NASW), the third indicates the soil class, the fourth the fundamental frequency (if any) estimated as HVSR from earthquakes (associated amplitude in the fifth column) or by HVNS where earthquakes were not available (associated amplitude in the sixth column)

Tab. 1 Data used in the study. See text for the details

				Peak	
Site	**Vs30**	**Soil**	**Freq (HZ)**	**HVSR**	**HVNR**
Aliano	S	B		1.50	
Anzi	S	A		1.50	
Avigliano	S	C	1.19	3.07	
Balvano	S	B	2.00	3.00	
Cagli Municipio	H	B	3.38	2.79	
Cagli S.Geronzio	H	A		1.50	
Cagli Vigili del Fuoco	H	C	4.16	3.59	
Castelluccio Inferiore	H	B	1.19	5.28	
Castelsaraceno	H	B			1.50
Gorgoglione	S	A	4.87	3.09	
Guardia	S	A	2.01	2.59	
Lagonegro	H	C	2.50		2.11
Maratea	H	C	3.66		4.60
Marsico Vetere	S	A	2.30	3.00	
Matera	H	C	1.09		5.56
Offida Rocca	H	B	1.48	2.06	
Offida Cappuccini	H	B	2.24	3.54	
Offida Municipio	H	C	1.82	2.12	
Offida Stadio	H	B	1.20	2.38	
Passo di Treia	H	B	3.38	3.54	
Pescopagano	S	D	1.41	2.70	
Potenza Campus	H	B	4.31	2.41	
Potenza Viale UNICEF	H	B	4.19		4.34
Rapolla	S	D	0.70	2.50	
Rotonda Alveo Mercure	H	B	0.66		3.74
Rotonda Il Cugno	H	C	2.72		3.07
Ruvo Monte	S	C	4.08	2.81	
S.Fele	S	A		1.50	
Senigallia Marchetti	H	C		1.50	
Senigallia Saline	H	C	2.40	4.25	
Senigallia Stadio	H	C	5.81	2.67	
Senise Sinnica	H	C	2.50		2.80
Serra de'Conti Deposito	H	B	1.48	2.33	
Sera de'Conti Municipio	H	B		1.50	
Sera de'Conti Scuola	H	B	1.48	2.34	
Tito Scalo	H	D	1.17	4.54	
Trecchina Balla con i Lupi	H	C	3.09		4.82
Trecchina PIP	H	B	0.59		3.85
Treia Carabinieri	H	B	2.75	2.34	
Treia Casa Riposo	H	B	0.98	2.10	
Tricarico Carmine	S	A	0.83	2.30	
Venosa	S	B	0.43	2.79	
Viggianello Pezzo la Corte	H	C	0.53		5.77
Viggianello Torbolo	H	C	0.34		6.19
Villa d'Agri Barricelle	S	C	3.50	3.00	
Villa d'Agri Scuola	S	C	1.18	2.90	

The first analysis performed was the grouping of Vs30 profiles according to the soil classification scheme, where class A has Vs30>800 m/s, B has 360<Vs30<800 m/s, C has 180<Vs30<360 m/s and D has Vs30<180 m/s. In our study we did not encounter E type sites. Fig. 1 reports the Vs profiles grouped by soil class, with superimposed the interpolated profiles according to power increase of velocity as a function of depth.

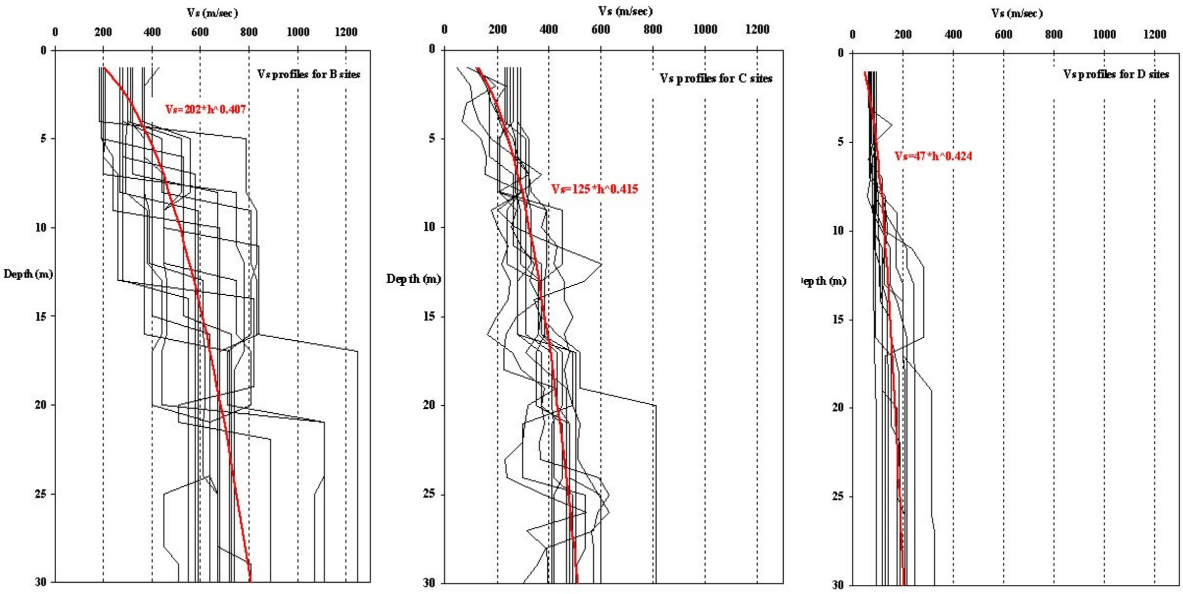

Fig. 1 Vs profiles grouped by soil class. Red lines are interpolated profiles.

Three things are worth noting: the larger variability of sites belonging to class B due to larger velocity range, the fact that only 5 sites reach 800 m/s (*i.e.* bedrock) within the first 30 m, and that the two parameters of the interpolating equations are inversely correlated as suggested by other authors (Albarello, 2006; personal communication). We then analysed the scatter of amplification as a function of soil category (Fig 2).

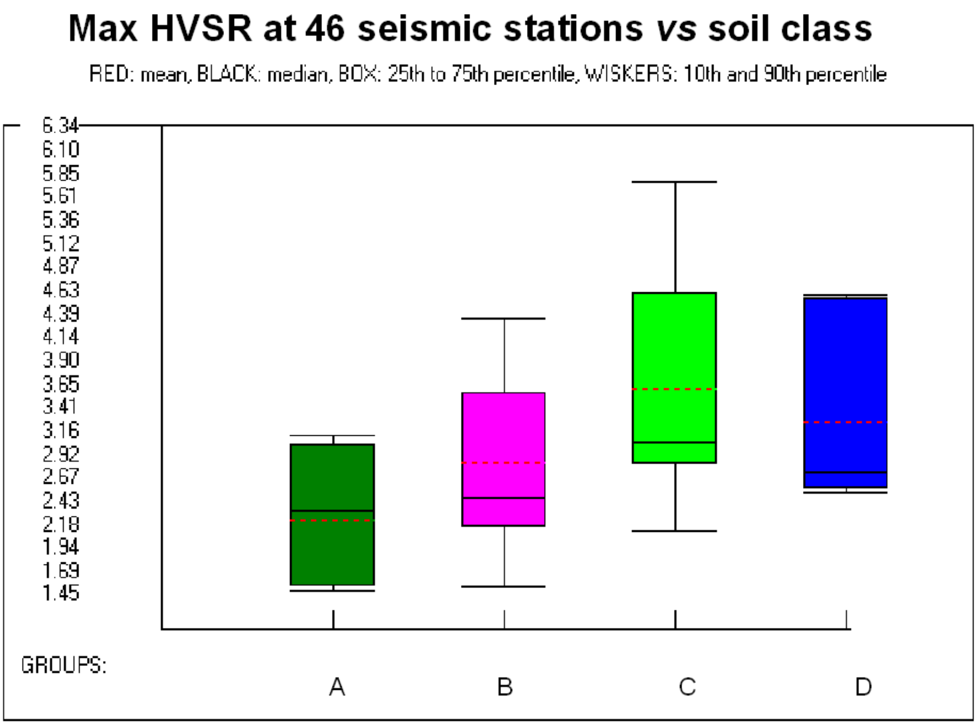

Fig. 2 Distribution of maximum amplitude of HVSR and HVNR grouped by soil classes.

Both average and median are increasing with soil category but the median of class A and median of class B are almost the same. There are several sites belonging to class B and few of class C sites that do not show amplification (HVSR<2). Finally, there are few sites in class D for a meaningful statistic, but they show less amplification than class C.
Fig. 3 is a pie diagram reporting the percentages of sites showing expected or unexpected behaviour.

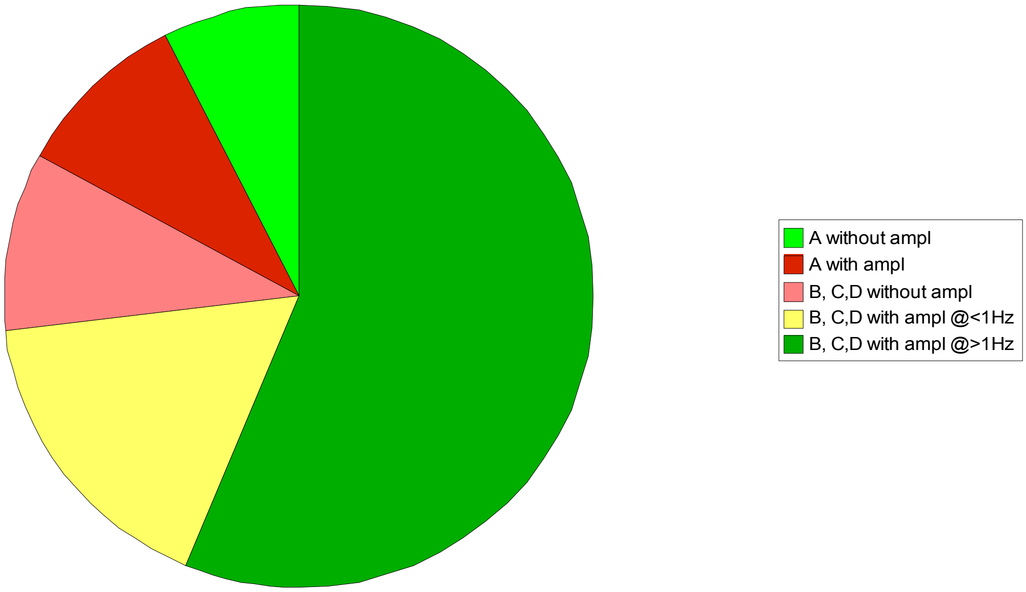

Fig. 3 Distribution of observed cases according to compliance or failure.

In 1 out of 5 cases there are amplifications where not expected or vice-versa. If we include the occurrence of amplification at low frequencies where not expected, the percentage of sites with problems reaches 36%.
Fig 4 shows the distribution of amplitude *vs.* frequency for the different soil classes.

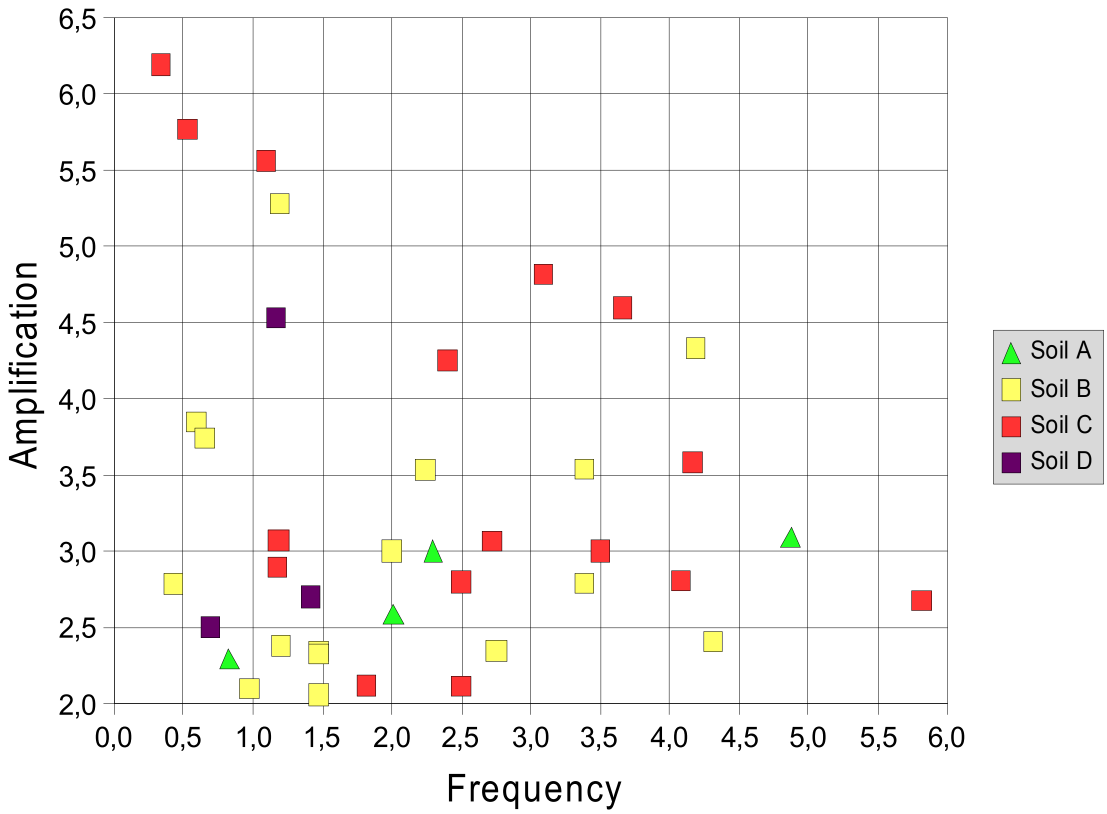

Fig. 4 Distribution of amplitude vs. frequency for different soil classes.

There is no clear correlation between frequency and amplification for different soil classes. Large amplifications at low frequencies occur at sites that are located within large sedimentary basins. This is surprising, because being HVSRs, these amplifications should be connected with 1-d effects and not with 2-d effects.
At this point we tried to answer the second question outlined in the introduction: in the Italian Seismic Code, is the grouping of Vs30 in different soil classes and relevant spectra adequate?
We then plotted the observed amplification *vs*. Vs30, without any grouping *a priori* (Fig. 5).

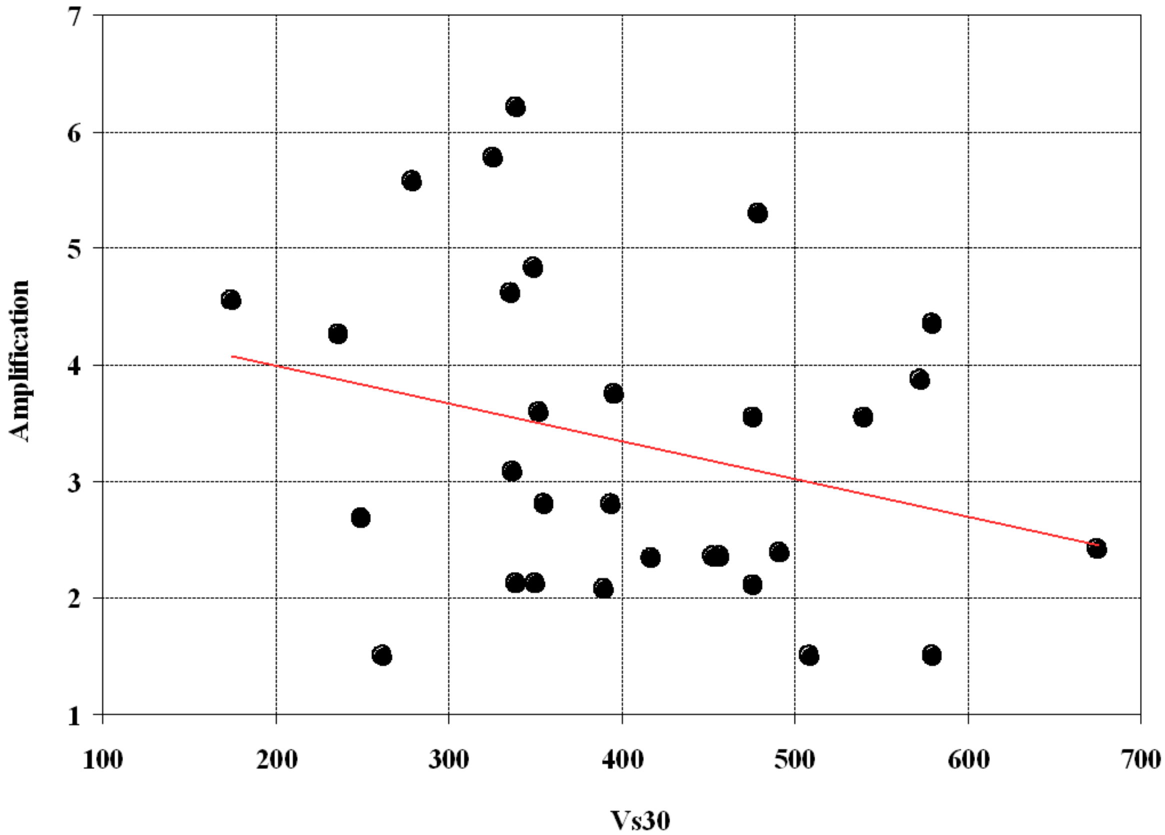

Fig. 5 Correlation between Vs30 and amplification, for D-H only.

We performed this analysis just for the best quality data, that is borehole profiles for class B and C only. There is a slight correlation between Vs30 and amplification, with a Spearman Rank Correlation = 0.239, that passes the significativity test at just 80% confidence level.
For the same reduced data sample, we perform a comparison between the observed spectra and the ones provided by the Code. To perform this check, we normalised the observations determining a statistic ε defined as

ε =[(Code spectrum B/ Code spectrum A)-mean observed B]/S.D. observed B (1)

Fig. 6 reports the result of the comparison. For soil category C, the building code underestimates the average observed amplification in the range 0.3-5 Hz, never exceeding 1 standard deviation of the distribution of the observed amplification functions. For frequencies higher than 5 Hz, the code is over-conservative, exceeding 1 standard deviation in the range 7.5-8.5 Hz
For soil category B, the building code underestimates the average observed amplification in the range 0.3-10 Hz, exceeding 1 standard deviation between 2.5-3.5 Hz.

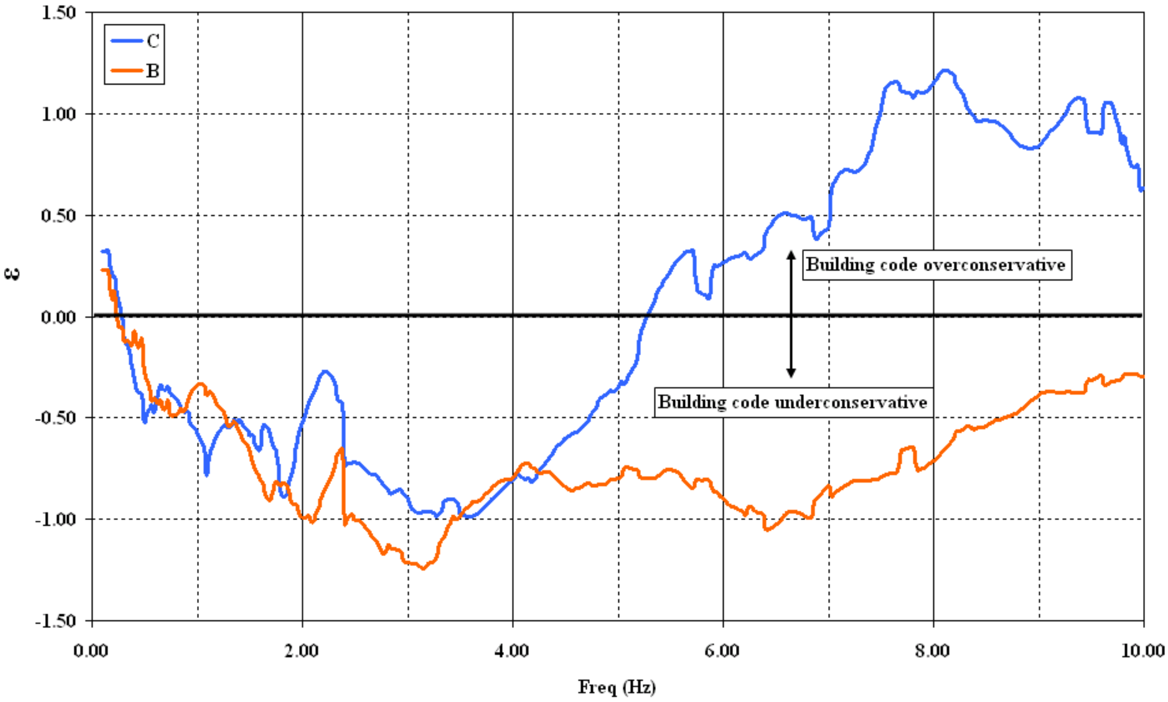

Fig. 6 Plot of the statistic estimated according with eq. 1.

3. DISCUSSION AND CONCLUSIONS

The general explanation why Vs30 may fail to correctly predict site amplification at a site was already given by Wald & Mori (2000): "*The disparity between observed and predicted amplifications appears to be a result of oversimplification inherent in the amplification estimation methods, such as... the smoothing effect of using an average velocity, limiting the properties considered to the uppermost 30 m of material, and complexities in the wave propagation that are not addressed by these methods*". We tried to identify if there are common characteristics for sites in Italy where Vs30 works fine or not.
The sites classified as Class A that show unexpected amplification are not affected by topographic effect, being mostly on hill flanks. A more probable cause is the possible presence of different degrees of rock fracturation, also induced by faults. A good example of this kind of situation is given by Martino *et al*. (2006) for Cerreto di Spoleto (Italy). A case of unexpected amplification is due to velocity inversion. This is a widespread situation in Italy. Ancient settlements took place on slices of rigid material overlying soft sediments: those remnants were the most suitable place to build a village. In southern Tuscany and Umbria and northern Latium, strata of quaternary volcanic products rest atop softer sediments; in the Apulia foredeep, well-cemented conglomerates overlay deep strata of clay and sand. The rigid top may well exceed 30 m, making the Vs30 estimate both difficult to obtain and meaningless at the same time.
The sites B and C that do not show any amplification are located on very deep basins with a probable low impedance contrast at the sediment-bedrock interface. In some cases the fundamental frequency is lower than expected by the Code, so the general pattern is an underestimation by the Code at frequency below 5 Hz. In either instances, the presence or not of a clear fundamental frequency with a strong amplification is due to cemented strata somewhere in the stratigraphic sequence, with very little importance of the Vs in the first meters. The Po plain, the Sant'Arcangelo Basin and the Adriatic foredeep are places were this phenomenon may occur. We have seen the best example of it in the city of Senigallia: all the site are classified as C, but some show amplification higher than expected while others have flat spectrum. The quaternary clay and sand deposits overlay Pliocene marls with almost no velocity contrast at 600 m/s. The limestones are more than 1.000 m deep. The amplification is due to the presence or not of compacted gravels strata in the first 30 m.
We would advise practitioners to be cautious when using Vs30. The Italian Building Code recommends to perform microzonation studies and to use Vs30 if no other data are available. Especially for public buildings, we recommend to try to record weak motions at the site of interest. Italy is a country with a diffused seismicity

allowing for short recording periods, and the cost of a basic seismometer or accelerometers equals two 30 m drillings plus down-hole test performed by contractors. At even lower cost, HVNR should be performed in sites where “rocky” appearance might suggest avoiding very expensive drillings thought to be useless.
We expect to obtain more data by ongoing projects that should double the data base of observation in the next two years, including sites on unstable slopes and karst areas, other two situations very common in Italy.

4. ACKNOWLEDGEMENTS

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